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The understanding of MeV electron beam propagation in the Earth's atmosphere and ionosphere has progressed substantially due to the completion of the author's doctoral research under the AASERT program, and a summary of results is presented in this report. A model based on several established analytical computational techniques has been developed to study the interactions of relativistic electron beams with the Earth's upper atmosphere and ionosphere. The emphasis is on the analysis of active experiments involving beams launched from a satellite in Low Earth Orbit or from a suborbital sounding rockets. The Beam-Atmosphere Interaction forms a subset of physical phenomena associated with the injection of charged particle beams from a spacecraft. The present study extends the analysis of the BAI from the keV range of past experiments, and it is motivated in part by the recent advances in technology which allow MeV electron beams to be launched from spacecraft. The model is designed to accept beam and environmental parameters as input, such as beam current, energy, and mean divergence, and to compute quantities of interest resulting from the relativistic BAI as output, such as ionization and bremsstrahlung emissions.

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AUGMENTATION OF

HIGH-ENERGY BEAM-INDUCED

IONOSPHERIC MODIFICATION EXPERIMENT

Final Technical Report

Prepared for

Air Force Office of Scientific Research

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by

Linda Habash Krause

30 November 98

Augmentation of

High-Energy Beam-Induced

Ionospheric Modification Experiment

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ABSTRACT:

The understanding of MeV electron beam propagation in the Earth's atmosphere and ionosphere has progressed substantially due to the completion of the author's doctoral research under the AASERT program, and a summary of results is presented in this report. A model based on several established analytical computational techniques has been developed to study the interaction of relativistic ($E \sim$ MeV) electron beams with the Earth's upper atmosphere and ionosphere. The emphasis is on the analysis of active experiments involving beams launched from a satellite in Low Earth Orbit (LEO) or from a suborbital sounding rocket. The Beam-Atmosphere Interaction (BAI) forms a subset of physical phenomena associated with the injection of charged particle beams from a spacecraft. The present study extends the analysis of the BAI from the keV range of past experiments, and it is motivated in part by the recent advances in technology which allow MeV electron beams to be launched from spacecraft. The model is designed to accept beam and environmental parameters as input, such as beam current, energy, and mean divergence, and to compute quantities of interest resulting from the relativistic BAI as output, such as ionization and bremsstrahlung emissions. The BAI is examined by first computing the electron beam energy loss using the Continuous Slowing Down Approximation (CSDA) and the beam cross sectional area by using the envelope equations which describe beam dynamics in the paraxial approximation. These results are used to complete a first-order stability analysis associated with the Beam-Plasma Interaction (BPI) and to calculate secondary electron fluxes resulting from electron-impact ionization. With a steady-state relativistic electron beam source, secondary electrons will cascade in energy until an equilibrium is reached. Model results for beam energies from 1 to 100 MeV are in reasonable agreement with previously established values of the collisional range and fractional energy loss due to radiative processes. The stability analysis shows that beams of lower current and higher energy and divergence are less susceptible to instability, and that the Earth's magnetic field plays a significant role in stability against certain transverse modes. As a sample of practical application of the model, bremsstrahlung fluxes incident on detectors onboard a satellite in LEO were compared with those incident on balloon detectors. Future potential applications include analysis of stratospheric odd-nitrogen production from relativistic electron precipitation events and ionospheric modification due to sprite propagation.

CONTENTS

1. INTRODUCTION

The study of propagation of Relativistic Electron Beams (REB's) in the terrestrial space environment is of fundamental interest to the upper atmosphere and space plasma communities. Ionospheric modification by beams of this energy has been studied by *Banks et al.* [1987, 1990] who characterized the significant ionization and steep potential gradients resulting from the interaction of the relativistic (MeV) beams with the surrounding environment. These beams are capable of achieving deep penetration into the lower ionosphere and even into the upper stratosphere when fired directly downwards along the Earth's magnetic field. It has also been shown that beam confinement by the external axial magnetic field significantly reduces the amount of radial expansion due to small-angle scattering and inelastic collision losses, constraining the beam's radius to be less than its gyroradius and a 90° pitch angle [*Neubert et al.*, 1996].

The Spaceborne Linear Accelerator System (SLINAC) is a program which is designed to demostrate the feasibility of injecting relativistic ($\sim$ MeV) electron beams into the earth's upper atmosphere/ionosphere. Motivating forces behind this mission include [*Jost*, 1993]:

- Upper Atmosphere/Ionosphere/Magnetosphere Research

- Orbital Debris Detection and Mitigation

- Atmospheric Ozone Depletion Monitoring and Mitigation

- RF Scattering Screens

- Department of Energy Directed Considerations

In order to guarantee a successful mission in which the heritage of this accelerator may be established, it is useful to quantify the beam propagation characteristics which are expected during an active experiment in the terrestrial space environment. Specifically, the areas of interest covered by this study include:

- **Analytical Description of Beam Propagation.** As an extension to the study by *Neubert et al.* [1996], the beam envelope equations have been used to predict beam propagation characteristics of interest (energy, radius, divergence) as a function of altitude over a variety of injection parameters, including beam energy (1-100 MeV), divergence (0.01-0.1 radians), and

current (0.1-10^4 A). Effects of beam-generated electric and magnetic fields were included in the analysis.

- **Beam-Plasma Interactions (BPI).** When high current ($I \gtrsim 100$ A) beams are considered, it is appropriate to examine the interaction of the beam with the surrounding space plasma. A first-order analysis of the BPI was performed for REB's propagating in a model terrestrial ionospheric environment.

- **Diagnostics for Active Space Experiments with REB's.** The Relativistic Beam-Atmosphere Interactions (RelBAI) model has been constructed in order to provide scientific and technological investigators with a tool to quantify physical signatures, such as optical emissions and ionization, resulting from the REB precipitation in a model atmosphere. This model provides a means of predicting the intensity of these products which would aid in the selection of the appropriate instrumentation for detection and chracterization of a propagating REB during an actual test in space.

This paper is meant to give a brief summary of some of the research completed under this AASERT contract and suggestions for continuation of this research in future studies. A list of publications completed during this contract is also provided.

2. STUDY SUMMARY

2.1. Relativistic Beam-Atmosphere Interactions

The RelBAI model was developed to provide a technique by which detailed quantities of the relativistic BAI may be computed analytically. The model accepts as inputs the injection energy, divergence, and current of a relativistic electron beam which propagates through a collisional atmosphere; model outputs include steady-state rates of ionization, bremsstrahlung, and atomic/molecular excited state production, all as a function of altitude. The model was designed to be modular in nature, which facilitates the specialization of the model by allowing investigators to integrate new modules as needed. As one example of a specialized application, the bremsstrahlung fluxes incident on detectors onboard LEO satellites and on balloons were computed for a 5 MeV electron beam slowing down in a model neutral atmosphere.

The RelBAI computation began with the calculation of the loss of beam electron energy in the Continuous Slowing Down Approximation (CSDA) as the beam penetrates the collisional atmosphere. The Earth's magnetic field is the principle focusing mechanism which counteracts the defocusing effects of collisions with the neutral atmosphere. It was shown that significant radial expansion of the beam occurs lower in altitude for beams of higher energy, which is consistent with the decrease in the interaction cross section with increasing primary electron energy. The penetration range into the atmosphere increased monotonically with beam energy, and the relationship between the beam energy and range found in this study is in general agreement with the results of *Berger and Seltzer* [1964], a 1-D treatment of the collisional stopping process. Thus, the current model supports the results of the 1-D problem. However, since the model here is for a 2-D system, it it also includes the radial expansion in the description of the degradation of the beam integrity as it propagates through the atmosphere, representing an extension to the 1-D analysis. See *Habash Krause* [1998a] for details.

2.2. Relativistic Beam-Plasma Interactions

The results from the beam degradation computations were used in a stability analysis for the purpose of identifying conditions in which instability threatens to disrupt beam propagation. Four instabilities were considered, including the electron-electron two-stream, the Weibel filamentation, the ion hose, and the resistive hose modes. In theory, keeping a beam's pulse length significantly shorter than the growth period of the instability should prevent disruption due to the instability. This holds true for

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absolute instabilities, but in fact, the instabilities examined here may be convective. Nonetheless, the instability growth periods computed here assist with a first-order analysis of the effects of beam paramters and environmental conditions on the relative importance of these instabilities. Characteristic growth periods were computed for the two-stream and both hose modes, and an absolute stability condition was checked for filamentation. It was found that all beams under consideration were stable against filamentation, but some of the beams may be subject to the two-stream, ion hose, and resistive hose modes under certain conditions. For example, for beam pulse lengths on the order of a few microseconds, beams with an energy of 10 MeV, a divergence of 0.1 radians, and a current of 10 kA may be susceptible to any of these three modes since the characteristic growth periods are on the order of a few microseconds. Here, it should be noted that the stability analysis makes use of the results of radial expansion which were computed under the assumption that the beams were indeed stable. Beams which are affected by instability may experience emittance growth or a loss of axial energy, both of which have implications for the accuracy of the computations of beam degradation which were performed with the assumption of stability. Thus, this method is inappropriate for conducting an analysis of unstable beams. For a proper treatment of beams which are expected to be subject to instability, the beam degradation due to collisional processes must be computed self-consistently with the computations of growth of oscillations which are associated with the instability. See *Habash Krause* [1997b] for details.

2.3. Beam Diagnostics

The results from the beam degradation analysis are used for the computation of the ionization and bremsstrahlung. There is a high-energy component of secondary electrons which is responsible for a source of bremsstrahlung. However, it was found that even though a large number of high-energy secondaries were created, the bremsstrahlung resulting from these electrons is significantly lower in intensity than that from the beam primaries. The secondary electrons are allowed to cascade in energy until they are thermalized; in the process, production of excited states and further ionization occur. The computations of bremsstrahlung fluxes incident on detectors at satellite and balloon altitudes showed that for optimal detection, balloons in close proximity to the beam should be used. If satellite detectors are used, then the detection of the photons actually improves when the horizontal displacement between the beam and detector increases from directly overhead (which is a local minima) to an example displacement of 60 km away. See *Habash Krause* [1998a, 1998b] for details.

2.4. Recommendations for Future Work

There are several recommendations for extension and improvement of the model. First, the accumulation and implementation of more accurate cross sections is an ongoing process since continuous

progress in experimental work naturally results in updated information. Secondly, it would be interesting to investigate the effects of an axial electric field. Such a field would be responsible for the acceleration of beam electrons, possibly to the point of the runaway condition. The field may also play an important role in the focusing of the beam. In order to account for an axial electric field, the paraxial ray equation must be modified to include the appropriate term. In addition, electron transport would be expected to play a significant role in the BAI. It would be interesting to modify the equations of electron transport in the two stream approximation [*Nagy and Banks*, 1970] to be time-dependent in order to handle the effects of an electric field. Finally, more processes need to be included in the model, such as spontaneous radiative de-excitation, molecular dissociation, quenching, and charge exchange.

With various forms of extension, the model can be used to assist in the study of several items of interest in space science research. For example, to support an active mission in which MeV electron beams are launched from a spacecraft, it would be helpful to have a prediction of optical emissions to aid in the design of a diagnostic system. For this purpose, optical emission transition probabilities would be necessary, as well as the inclusion of any other processes which would lead to loss of excited states (such as quenching). Another useful application would be the analysis of the influence of backwards-ejected secondary electrons from a downward propagating beam on the magnetospheric trapped population. The energetic trapped population resulting from relativistic electron beam propagation in the magnetosphere is currently under investigation using techniques developed by Khazanov et al. [1995] and Khazanov and Liemohn [1996], and the model can aid in the specification of the addition of energetic secondaries to this population resulting from the BAI of the population of primary beam electrons which happened to scatter into the loss cone. Furthermore, with the addition of the time-dependent component of electron transport, electric fields can be included which would assist in the analysis of the contribution of the runaway electron process in the generation of sprites. It is known that gamma-ray flashes are associated with electrical discharges in the upper atmosphere, and a concentrated effort is underway to plan for satellite-based x-ray detectors with fine energy and spatial resolution in order to image these events [*Neubert*, 1998]. A prediction in the intensities of x- and gamma-ray bremsstrahlung and K-shell line emission would assist in the prediction of intensities for optimal detector selection, as well as assist in the interpretation of observed emissions. Finally, it would be interesting to investigate the creation of stratospheric odd nitrogen which results from the impact dissociation of molecular nitrogen in an effort to determine the effect of naturally occurring relativistic electron precipitation events on the creation of the odd nitrogen.

3. PUBLICATIONS

The following publications were a direct result from the research completed under the AASERT contract.

Habash Krause, L., B. E. Gilchrist, T. Neubert, Propagation dynamics of high-altitude relativistic electron beams, IEEE Trans. Plasma Sci., submitted, 1998.

Habash Krause, L. The interaction of relativistic electron beams with the near-Earth space environment, Ph.D. Dissertation, University of Michigan, 1998.

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Neubert, T., B. E. Gilchrist, S. Wilderman, L. Habash, and H. J. Wang, Relativistic Electron Beam Propagation in the Earth's Atmosphere: Modeling Results, *Geophys. Res. Lett. 23*, 1009-1012, 1996.

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